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Conjugate heat and mass transfer in drying: A modeling review

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ABSTRACT

Coupled transfer mechanisms are common in a variety of industrial operations, as in food drying, and their virtualization is becoming indispensable. In this paper one such situation, a rectangular food chunk exposed to heat and mass transfer by a turbulent cross flow of air in a channel ($Re \simeq 1 \cdot 10^4$), is investigated by modeling the transfer mechanisms (linked each other by evaporation) in conjunction with the inherent flow transport. This formulation is referred to as a conjugate problem.

In the present model, the most limiting parameters that commonly are employed in such studies can be disregarded, i.e. the empirical heat and mass transfer coefficients at the auxiliary air/substrate interface: they refer to unrealistical average conditions and unspecified geometry variations.

After proper literature evaluation, the solution of a benchmark drying problem is discussed by assessing the conjugate and coupled features of the analytical development, focusing on some transfer phenomena loci on the sample's exposed surface. It is shown that, in case of a finite protrusion with a unitary form factor (height equals streamwise thickness) the average Nusselt number of about 25 (resumed from associated literature) greatly overestimates the one computed based on the model, everywhere along the exposed surface and during process time: varying up to 6 times along the lateral edges and dropping down to an average value of about 6 after less than 2 h of treatment.

1. Introduction

Many processes involve simultaneous heating and drying of given 3D moist substrates placed in a bulk flow of working air, generally in the turbulent regime. In the process industry, one of the simplest configuration is with the substrates protruding in the flow, therefore altering (and partially blocking) the boundary layer. But in this case, strong finishing effects in drying and thermization are produced, that can be reflected even within the substrate itself. These effects are impossible to study by analytical methods, and prohibitive to attack with experimental procedures. That is why numerical computations of such complex processes, or virtualization, come into play.

This classical problem of momentum transfer over protrusions has been treated numerically by Shah and Ferziger (1997), for example. Coherent horseshoe vortices, separations and wakes are created that affect the other transfer phenomena (Fiebig, 1998). Even during steady flows, nonuniform variable thermal and moisture driving forces are therefore determined over, through and along the exposed surfaces, depending on the altered flow field, yielding for complex distributions of temperature and residual moisture. This situation, referred to as a conjugate problem, is reviewed in the present paper.

The quantitative study of the heat transfer has clearly preceded the one on moisture transfer. External flows have drawn considerable attention over the years. The protrusion geometry exploited in this paper also differs from other classical arrangement, as the so-called immersed body (Knudsen et al., 1997; Culham et al., 2001). Average heat transfer for isoflux rectangular semicylinders (sitting on the floor, with their axis normal to the flow) was experimentally performed first by Roeller et al. (1991), in the $\overline{Nu} = aRe^b$ form, accounting for flow three-dimensionality and blockage.

A conjugate heat transfer is the one that analyzes the heat transfer simultaneously in both solid and fluid phases (Joshi and Nakayama, 2003), and the solution for temperature is determined with no need for empirical assumptions at the interface: isothermal or isoflux assumptions are no longer needed. In other words, the

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